Kaon Physics

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1 Introduction

Kaon decays have played a key role in shaping the Standard Model (SM). Prominent examples include the introduction of internal "flavor" quantum numbers (strangeness), parity violation ($K \to 2\pi, 3\pi$ puzzle), quark mixing, meson-antimeson oscillations, discovery of CP violation, suppression of flavor-changing neutral currents (FCNC), discovery of the GIM mechanism and prediction of charm. Now and looking ahead, kaons continue to have high impact in constraining the flavor sector of possible extensions of the SM.

In the arena of kaon decays, a prominent role is played by the FCNC modes mediated by the quark-level processes $s \to d(\gamma, \ell^+\ell^-, \nu\bar{\nu})$, and in particular the four theoretically cleanest modes $K^+ \to \pi^+\nu\bar{\nu}$ $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0 e^+e^-$, $K_L \to \pi^0\mu^+\mu^-$. Because of the peculiar suppression of the SM amplitude (loop level proportional to V_{us}^5) which in general is not present in SM extensions, kaon FCNC modes offer a unique window on the flavor structure of SM extensions. This argument by itself provides a strong and model-independent motivation to study these modes, in the LHC era: rare kaon decays can teach us something about the flavor structure of SM extensions that are in general not accessible at high-energy colliders.

The actual "discovery potential" depends on the precision of the prediction for these rare kaon decays in the SM, the level of constraints from other observables and how well we can measure their BRs.

1.1 Rare kaon decays in the Standard Model: current status and future forecast

State-of-the-art predictions are summarized in Table 1 and show our current knowledge of the BRs: $K^+ \to \pi^+\nu\bar{\nu}$ at the 10% level, $K_L \to \pi^0\nu\bar{\nu}$ at the 15% level, and $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$ at the 25-30% level. In the charged lepton modes, the uncertainty is dominated by long distance contributions which are parameterized in terms of the rates of other decays (such as $K_S \to \pi^0\ell^+\ell^-$). In the neutrino modes, the irreducible theoretical uncertainty is a small fraction of the total uncertainty, which is dominated by the uncertainty in the CKM parameters that enter the prediction. It can be forecast that in the next decade progress in lattice QCD combined with progress in B meson measurements (LHCb and Super-Belle) will allow one to reduce the uncertainty on both $K \to \pi\nu\bar{\nu}$ modes to the 5% level. Substantial improvements in $K_L \to \pi^0\ell^+\ell^-$ will have to rely on lattice QCD computations, requiring the evaluation of bi-local operators. Exploratory steps exist in this direction, but these involve new techniques and it is hard to forecast the level of uncertainty that can be achieved, even in a ten-year timescale. Therefore, from a theory perspective, the golden modes remain both $K \to \pi\nu\bar{\nu}$ decays, because they have small long-distance contamination (negligible in the CP violating K_L mode). Note that $K \to \pi\nu\bar{\nu}$ are predicted with a precision surpassing any other FCNC process involving quarks.

1.2 Beyond the Standard Model physics reach

The BSM reach of rare FCNC kaon decays has received significant attention in the literature, through both explicit model analyses and model-independent approaches based on effective field theory. In the

mode	Standard Model	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}$	$7.81(75)(29) \times 10^{-11}$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ E787/949
$K_L \to \pi^0 \nu\bar{\nu}$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a
$K_L \to \pi^0 e^+ e^-$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 28 \times 10^{-11}$ KTEV
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 38 \times 10^{-11}$ KTEV

Table 1: Summary of current SM predictions and experimental limits for the four cleanest rare K decays. In the SM predictions, the first error is parametric, the second denotes the intrinsic theoretical uncertainty.

absence of an emerging candidate for the TeV extension of the SM (this might change as more data from the LHC are analyzed) the case for discovery potential and model-discriminating power can be presented very efficiently in terms of an effective field theory (EFT) approach to BSM physics. In this approach, one parameterizes the effect of new heavy particles in terms of local operators which carry dimensionful couplings, suppressed by inverse powers of the heavy new physics mass scale. The important point is that the EFT approach allows us to make statements that apply to classes of models, not just any specific SM extension. In this context, one can ask two important questions: (i) how large of a deviation from the SM can we expect in rare decays from existing constraints? (ii) if a given class of operators dominates, what pattern of deviations from the SM can we expect in various rare kaon decays? Concerning the golden modes, the main conclusion of this analysis is that assuming the dominance of "Z-penguin" operators (which is realized in many models including MSSM and Randall-Sundrum warped extra dimensions models), then ϵ'/ϵ provides the strongest constraint on the CP violating mode $K_L \to \pi^0 \nu\bar{\nu}$. This is illustrated in Fig 1, where one can see that the requirement $\epsilon'/\epsilon \in [0.2, 5](\epsilon'/\epsilon)_{SM}$ limits deviations in the $K_L \to \pi^0 \nu\bar{\nu}$ to be at most 50%. On the other hand, larger deviations in the CP conserving mode $K^+ \to \pi^+ \nu\bar{\nu}$ are still allowed. This conclusion holds in all models in which the Z-penguin provides the dominant contribution to rare decays and is one of the main drivers to assess an interesting target sensitivity for $K_L \to \pi^0 \nu\bar{\nu}$ experiments.

Rare kaon decays have been extensively studied within well motivated extensions of the SM, such as SUSY and warped extra dimensions (Randall-Sundrum) models. In all cases, deviations from the SM can be sizable and perhaps most importantly the correlations between various rare K decays are essential in discriminating among models. It is also worth stressing that rare $K \to \pi\nu\bar{\nu}$ can also probe the existence of light states very weakly coupled to the SM appearing in various hidden sector models, through the experimental signature $K \to \pi$ plus missing energy and distortions to the pion spectrum.

1.3 Beyond FCNC

Besides the FCNC modes, kaon decays also provide exquisite probes of the charged-current (CC) sector of SM extensions, probing to scales of TeV or above. Theoretically, the cleanest probes are (i) ratio $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, which test lepton universality, scalar, and tensor CC interactions; (ii) the transverse muon polarization P_μ^T in the semi-leptonic decay $K^+ \to \pi^0 \mu^+ \nu_\mu$, which is sensitive to BSM sources of CP violation in scalar CC operators. In both cases there is a clean discovery window provided by the precise SM theoretical prediction (R_K) and by the fact that in the SM P_μ^T is generated only by small and theoretically known final state interactions.

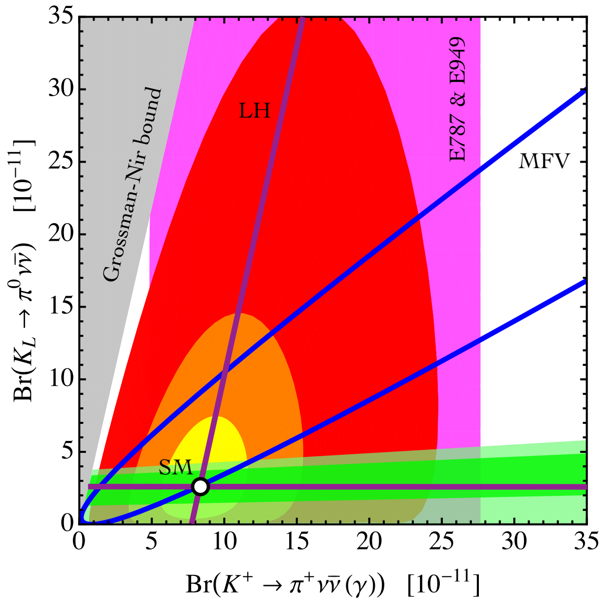

Figure 1: Predictions for the $K \to \pi\nu\bar{\nu}$ branching ratios assuming different types of NP contributions. The SM point is indicated by a white dot with black border. The yellow, orange, and red shaded contours correspond to BSM contributions to the Z-penguin less than 50%, 100%, 200% of the SM contribution to the Z-penguin. the magenta band indicates the 68% confidence level (CL) constraint on $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}(\gamma))$ from experiment [**?**], and the gray area is theoretically inaccessible. The blue parabola represents the subspace accessible to MFV models. The purple straight lines represent the subspace accessible in models that have only LH currents, due to the constraint from ϵ_K [**?**]. The green band represents the region accessible after taking into account the correlation of $K_L \to \pi^0\nu\bar{\nu}$ with ϵ'_K/ϵ_K: the (light) dark band corresponds to predictions of ϵ'_K/ϵ_K within a factor of (5) 2 of the experimental value, using central values for the hadronic matrix elements.

2 Experimental Program

Following the termination of a world-class kaon program in the US at the turn of the millenium, leadership in kaon physics has shifted to Europe and Japan.

The NA62 experiment at CERN is an in-flight measurement of $K^+ \to \pi^+\nu\bar{\nu}$ that will finish commissioning at the end of 2013 and start physics running simultaneous with LHC operations in 2014. The NA62 goal is to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio with 10% precision along with a robust and diverse kaon physics program.

The KOTO experiment at JPARC is an in-flight measurement of $K^0_L \to \pi^0\nu\bar{\nu}$. Significant experience and a better understanding of the backgrounds to this rare decay mode were obtained in its predecessor E391a. The anticipated experimental sensitivity is a few SM signal events in three years of running with 300kW of beam. Commissioning runs were undertaken in 2012 and 2013, but the longer term performance of the experiment will depend upon beam power evolution of the JPARC accelerator.

The TREK Experiment at JPARC will search for T violation in charged kaon decays by measuring the polarization asymmetry in $K^+ \to \pi^0\mu^+\nu_m$ decays. TREK needs at least 100 kW (proposal assumes 270 kW) for this measurement. While the accelerator is running at lower power, collaborators have proposed a search for lepton flavor universality violation through the measurement of $\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ at the 0.2% level, which will use much of the TREK apparatus and requires only 30 kW of beam power and will be ready to run in 2015. The uncertainty of the JPARC beam power profile and potential conflicts for beamline real estate make the long term future of the TREK experiment unclear.

The ORKA experiment is proposed to measure $K^+ \to \pi^+\nu\bar{\nu}$ with 1000 event sensitivity at the Main Injector. ORKA is a stopped kaon experiment that builds on the experience of the E787/949 experiments at Brookhaven. Like NA62, ORKA offers a wide variety of measurements beyond the $K^+ \to \pi^+\nu\bar{\nu}$ mode.

By the end of this decade we might expect that NA62 will have measured the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio to 10% precision and KOTO will have observed the $K_L^0 \to \pi^0\nu\bar{\nu}$ mode with standard model sensitivity. ORKA and TREK would be in progress. The physics reach in the kaon sector is well motivated and will continue to be of interest for the foreseeable future. Therefore, there are significant opportunities for important measurements in the kaon sector at Project-X.

2.1 Project-X Kaon Program

The flagship experiment of the Project-X kaon era would measure the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio with 5% precision. This effort will build on the KOTO experience, benefit from detector R&D and take advantage of the beam power and flexibility provided by Stage 2 of Project-X.

The KOPIO initiative [**?**] proposed to measure $K_L^0 \to \pi^0\nu\bar{\nu}$ with a SM sensitivity of 100 events at the BNL Alternating Gradient Synchrotron (AGS) as part of RSVP (Rare Symmetry Violating Processes) project. The experimental technique and sensitivity were well-developed and extensivity reviewed. KOPIO was designed to use a neutral beam at a 42° targeting angle produced by 24 GeV protons from the AGS. The neutral kaons would have an average momentum of 800 MeV/c with a range of 300–1200 MeV/c. A low momentum beam was critical for the Time-Of-Flight (TOF) strategy of the experiment.

The TOF technique is well-matched to the kaon momentum produced by the 3 GeV proton beam at Project-X. Performance of the TOF strategy was limited by the design bunch width of 200 ps at the AGS. The Project-X beam pulse timing, including target time slewing, is expected to be less than 50 ps and would substantially improve the momentum resolution and background rejection capability of the $K_L^0 \to \pi^0\nu\bar{\nu}$ experiment driven with the Project-X beam.

The AGS K_L yield per proton is 20× the Project-X yield; however, Project-X compensates with a 0.5 mA proton flux that is 150× the RSVP goal of 10^{14} protons every 5 seconds. Hence the neutral kaon flux would be 8× the AGS flux goal into the same beam acceptance. The nominal five-year Project-X run is 2.5× the duration of the KOPIO initiative at the AGS and hence the reach of a Project-X $K_L^0 \to \pi^0\nu\bar{\nu}$ experiment could be 20× greater than RSVP.

A TOF-based $K_L^0 \to \pi^0\nu\bar{\nu}$ experiment driven by Project-X would be re-optimized for the Project-X K_L momentum spectrum, TOF resolution and corresponding background rejection. It is likely that this optimization would result in a smaller neutral beam solid angle which would simplify the detector design, increase the acceptance and relax the requirement to tag photons in the fierce rate environment of the neutral beam. Optimizing the performance will probably require a proton pulse train frequency of 20-50

MHz and an individual proton pulse timing of $\sim$20 ps. Based on the E391a and KOTO experience, a careful design of the target and neutral beam channel is required to minimize the neutron halo. The high K_L beam flux, the potential of break-through improvements in TOF performance and calorimeter technology support the plausibility of a Day-1 $K_L^0 \to \pi^0 \nu\bar{\nu}$ experiment with $\sim$1000 SM event sensitivity.

In the case where a significant non-SM result were observed by ORKA [**?**], the $K^+ \to \pi^+ \nu\bar{\nu}$ decay mode could be studied with higher statistics with a K^+ beam driven by Project-X. The high-purity, low-momentum K^+ beam designed for ORKA could also serve experiments to precisely measure the polarization asymmetry in $K^+ \to \pi^0 \mu^+ \nu_m$ decays and to continue the search for lepton flavor universality violation through the measurement of $\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ at high precision.

Depending upon the outcome of the TREK experiment at JPARC, a T violation experiment would be an excellent candidate for Project-X, as would a multi-purpose experiment dedicated to rare modes that involve both charged and neutral particles in the final state. This experiment might be able to pursue $K_L \to \pi^0 \ell^+ \ell^-$ as well as many other radiative and leptonic modes.

3 Conclusion

TO BE REVISITED

To summarize, rare and not-so-rare kaon decays are extremely sensitive probes of the flavor and CP-violating sector of any SM extension. The $K \to \pi\nu\bar{\nu}$ remain the golden modes and offer a "win-win" opportunity for the future because: (i) sizable ($O(1)$) deviations from the SM are expected; (ii) even small deviations can be detected due to the precise theoretical predictions. Future searches (at Project-X) should aim for a sensitivity level of 10^3 SM events (few %) in both K^+ and K_L modes, so as to retain plenty of discovery potential in the K_L modes even in presence of the constraint from ϵ'/ϵ. We foresee the search for $K_L \to \pi^0 \nu\bar{\nu}$ as the flagship measurement of the kaon program at Project-X, with the potential to uncover novel BSM sources of CP violation. But we also stress the importance of pursuing the broadest possible set of measurements, so as to enhance the model discriminating power of Project-X.

The Project-X kaon program will benefit greatly from an ongiong R&D effort to produce hermetic, highly efficient low-energy calorimetry; high precision calorimetric timing; particle identification for π/μ and π/K separation at low energies; and very low mass tracking with excellent momentum and spatial resolution. Although R&D can move forward in the near term, there is a significant concern that domestic expertise in kaon physics will be completely depleted if there is no near-term kaon program in the U.S. As a consequence, the ORKA experiment at the Main Injector is an absolutely integral part of the Project-X kaon program. If ORKA does not run this decade, there will be little hope of carrying out the extremely challenging kaon program that the science motivates and Project-X can facilitate.

References

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